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Specification for a Standard Radar Sea Clutter Model

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1.0 INTRODUCTION

The purpose of this report is to document a radar sea clutter model for inclusion as a Navy standard model in the Oceanographic and Atmospheric Master Library (OAML).

The generalized form of the radar equation can be written as

$$P_r = \frac{P_t G^2 \lambda^2 L_s}{(4\pi)^3 R^4} \sigma_c F^4 \qquad \text{(W)} \qquad (1)$$

where P_r is power received, P_t is transmitted power, G is antenna gain, λ is radar wavelength, L_s is system losses, R is range, σ_c is average clutter cross section, and F is the pattern propagation factor. If the antenna pattern effects are separated from F, Eq. 1 becomes

$$P_r = \frac{P_t G^2 \lambda^2 L_s f(\alpha)^4}{(4\pi)^3 R^4} \sigma_c F^4 \qquad \text{(W)} \qquad (2)$$

where $f(\alpha)$ is the antenna pattern factor for angle α, and F is now the propagation factor. Sea clutter cross section can be factored further by

$$\sigma_c = \sigma^0 A_c \qquad (\mathrm{m}^2) \qquad (3)$$

where σ^0 is normalized radar reflectivity of the sea surface ($\mathrm{m}^2/\mathrm{m}^2$), and A_c is the radar's clutter resolution cell

$$A_c = \frac{c\tau}{2} \frac{\theta}{2\ln(2)} R \sec(\psi) \qquad (\mathrm{m}^2) \qquad (4)$$

In Eq. 4, c is the speed of light, τ is the radar's compressed pulse length (or pulse length if pulse compression is not used), θ is the horizontal beamwidth (one-way, 3 dB), and ψ is grazing angle at the surface. For angles of interest here, $\psi \leq 10$ degrees and sec $(\psi) \approx 1$. In the type of semiempirical sea clutter model being proposed here, the propagation factor is considered to be included in the models for σ_c ; that is, $\sigma^0 A_c F^4$ can be thought of as effective cross section, σ_c. Thus, the radar equation is now

$$P_r = \frac{P_t G^2 \lambda^2 L_s f(\alpha)^4}{(4\pi)^3 R^4} \sigma_c \qquad \text{(W)} \qquad (5)$$

and all of the environmental and propagation considerations are contained in the model of σ^0. An existing normalized sea clutter model[1] has been shown capable of approximating observed clutter data if grazing angles are calculated based upon typical surface-layer refractive conditions over the ocean.[2] The model proposed here combines this adaptation of the σ^0 model with the radar resolution cell, A_c, to provide a model of σ_c in Eq. 5 versus range under varying propagation conditions for typical radar frequencies.

In section 2.0, the inputs, outputs, and limits of the sea clutter model are defined. In section 3.0, the model is described in detail. In section 4.0, test data are shown to verify the proper operation of the computer program listed in the appendix.

2.0 INPUTS, OUTPUTS, AND LIMITS

Environmental measurements and radar system parameters are required to calculate the average sea clutter radar cross section as the output. The environmental input parameters are summarized in Table 1.

Table 1. Environmental input parameters.

Parameter	Limits	Precision
Evaporation duct height	0 to 40 m	0.1 m
Modified refractivity profile	0 to 10,000 m	1 m
	0 to 2000 *M*	1 M
Wind speed	0 to 25 m/s	1 m/s
Wind direction relative to antenna boresight	0 to 180 deg	5 deg

2.1 ENVIRONMENTAL PARAMETERS

2.1.1 Evaporation Duct Height

The evaporation duct height can be calculated from measurements of wind speed, air temperature, relative humidity, and sea surface temperature,[3] or derived from a statistical data base.[4] The evaporation duct height is used to generate a modified refractivity profile for the atmospheric surface layer. The M-profile is subsequently used in determining grazing angles at the sea surface for frequencies of 2 GHz and greater. The evaporation duct height is limited to 0 to 40 meters.

2.1.2 Modified Refractivity Profile

The modified refractivity profile is represented by couplets of height in meters and refractivity in *M*-units from the surface to some height greater than the radar altitude. This profile, which can be derived from radiosonde or refractometer measurements or a statistical data base,[4] is used in the model to calculate an effective earth radius for the determination of grazing angles at the sea surface for frequencies less than 2 GHz.

2.1.3 Wind Speed and Direction

Wind speed and direction can be measured by any typical cup or aerovane anemometer. The measurement should be made in a location that is representative of the wind flow over the ocean at the standard anemometer height (19.5 meters). The valid range of the windspeed is 0 to 25 m/s. Wind direction for the sea clutter model is defined relative to the direction in which the radar antenna is pointing; the measured wind direction must be converted to this definition in the range of 0 to 180 degrees. Wind speed is used to calculate a wind speed factor in the sea clutter model. Under the assumption of a fully risen sea and steady-state conditions, wind speed and wave height are highly correlated, and wind speed is used to calculate an average wave height for the interference factor. Under transient conditions, wave height and wind speed may not be well correlated, and the model could be modified to accept both wind speed and average wave height as inputs.

Wind direction relative to the radar antenna boresight is used to calculate an upwind/downwind factor that varies from a maximum looking into the wind to a minimum looking with the wind. An intermediate clutter level calculated in the crosswind direction (90 degrees) yields a level that is $\approx \pm 5$ dB of the clutter level in the upwind/downwind directions.

2.2 RADAR PARAMETERS

The required radar system parameters are summarized in Table 2. Antenna height, polarization, and radar frequency are used in the calculations of normalized radar cross section, σ^0. The horizontal beamwidth and compressed pulse length are used in the calculation of the radar clutter resolution cell. If the radar receiver does not use pulse compression, the pulse length is used.

Table 2. Radar system parameters.

Parameter	Limits	Precision
Antenna height	1 to 10000 m	1 m
Radar frequency	100 to 20000 MHz	1 MHz
Antenna polarization	H, V, C	*
Horizontal beamwidth	>0 to 45 deg	0.1 deg
Compressed pulse length	>0 to 1000 μs	0.1 μs
Maximum range	500 km	1 km

* H = horizontal, V = vertical, C = circular.

2.3 OUTPUT

The output of the sea clutter model is clutter level in decibels relative to a 1 m² target versus range in kilometers.

3.0 MODEL

The sea clutter model is composed of two main functions. First, grazing angle at the sea surface, ψ, is determined from inputs of evaporation duct height, δ, effective earth radius, a_e, radar antenna height, H_t, and radar frequency, f. Next, normalized radar cross section, σ^o, is calculated from inputs of grazing angle, wind speed, V_w, wind direction relative to the antenna, ϕ, radar frequency, and antenna polarization. The normalized radar cross section can then be used directly to calculate average radar cross section, σ_c, versus range out to the maximum range specified.

3.1 GRAZING ANGLE AT SEA SURFACE

At radar frequencies less than 2000 MHz, the effective earth radius is assumed to be the dominant factor in determining grazing angle versus range. The minimum grazing angle allowed is 1.745×10^{-3} radians (0.1 degree); the maximum grazing angle is 1.745×10^{-1} radians (10 degrees). The range, r, in kilometers at which a specific grazing angle occurs is determined from the quadratic formula

$$r = \frac{-b + \sqrt{b^2 - 4ac}}{2a} \quad \text{(km)} \tag{6}$$

with

$$a = 1$$
$$b = 2a_e\psi$$
$$c = -2a_eH_t/1000$$

where a_e is in kilometers, ψ is in radians, and H_t is in meters. The effective earth radius is determined by using subroutines MFROF, INSRT, PUSH, and GETK from the standard propagation model.[6] The elevation angle, α, at the antenna that corresponds to a given range is

$$\alpha = -\frac{H_t}{1000r} - \frac{r}{2a_e} \quad \text{(rad)} \tag{7}$$

Grazing angles at ranges intermediate to those corresponding to the maximum and minimum grazing angles are determined by

$$\psi = \frac{H_t}{1000r} + \frac{r}{2a_e} \quad \text{(rad)} \tag{8}$$

where range increments are 1/100 of the maximum range.

At radar frequencies of 2000 MHz and greater, the evaporation duct can have a significant effect on the variation of grazing angle versus range. Instead of an effective earth radius being used in the ray-optics calculations, a refractive profile for the evaporation duct must be generated. The M-value at the sea surface, M_0, is arbitrarily set equal to 340, and the profile is calculated from

$$M(z) = M_0 + 0.125z - 0.125\delta \ln\left(\frac{z + z_0}{z_0}\right) \tag{9}$$

where ln is the natural logarithm and

$$z = e^k, \quad k = -2, -1, 0, 1, 2, 3, 4$$

for heights, z, above the surface. The aerodynamic roughness of the sea surface, z_0, is assumed constant at 0.00015 meter. The minimum value in the evaporation duct profile occurs at the evaporation duct height (where $z = \delta$) and must also be included in the profile. (Note that Eq. 9 can be used to generate a profile with subrefractive layers if a negative δ is entered. The physical meaning of negative δ is the height at which dM/dz reaches a value of + 0.250M/m. However, the evaporation duct model[3] has been arbitrarily limited to positive duct heights.) To complete the profile and as a convenience for ray-optics calculations, the height of the radar is included in the height array and the M-value at the height of the radar is included in the M-array. This M-value is determined by linear interpolation between adjacent levels or extrapolation at 0.118 M/m above the last level in the profile.

The minimum elevation angle allowed is -1.745×10^{-1} radians (−10 degrees). The maximum elevation angle is calculated from

$$\alpha_{max} = -[2 \times 10^{-6}(M_{ht} - M_{min})]^{1/2} - 1 \times 10^{-6} \qquad \text{(rad)} \qquad (10)$$

where M_{ht} is the value of M at the radar antenna height and M_{min} is the minimum value of M_{min} in the profile below the height of the radar. If the radar height is less than the evaporation duct height, then

$$\alpha_{max} = -[2 \times 10^{-6}(M_{ht} - M_{\delta})]^{1/2} - 1 \times 10^{-6} \qquad \text{(rad)} \qquad (11)$$

where M_δ is the value of M at the evaporation duct height. The grazing angle corresponding to each elevation angle is

$$\psi = [\alpha^2 - 2 \times 10^{-6}(M_{ht} - M_0)]^{1/2} \qquad \text{(rad)} \qquad (12)$$

The elevation angle is gradually decreased between the maximum and minimum angles according to

$$\Delta\alpha = \frac{\alpha_{max} - \alpha_{min}}{d} \qquad \text{(rad)} \qquad (13)$$

where d has a value dependent upon the last value of ψ :

$\psi < 0.0175$	$d = 200$
$0.0175 \leq \psi < 0.08$	$d = 20$
$\psi \leq 0.08$	$d = 4$

The range corresponding to each elevation angle (and grazing angle) is determined by tracing a ray from the radar antenna height through the successive layers of the M-profile to the surface. For downgoing rays ($\alpha<0$), the angle, α', at the base of the layer is

$$\alpha' = -[\alpha^2 + 2 \times 10^{-6} dMdh(h_{i-1} - h_i)]^{1/2} \qquad \text{(rad)} \qquad (14)$$

and the range, r', traveled is

$$r' = r + \frac{\alpha' - \alpha}{1 \times 10^{-3} dMdh} \qquad \text{(rad)} \qquad (15)$$

where $dMdh$ is the refractive gradient (M/m) of the layer. If the radar antenna height is less than the evaporation duct height, the rays are initially upgoing and are traced to the level of the evaporation duct height. For upgoing rays, the elevation angle at the top of the layer is

$$\alpha' = [\alpha^2 + 2 \times 10^{-6} dMdh(h_{i+1} - h_i)]^{1/2} \qquad \text{(rad)} \qquad (16)$$

and r' is calculated as above. Once the range traveled by the ray to the height of the evaporation duct is known, it is doubled and ray tracing continues with downgoing rays at the radar antenna height (Fig. 1).

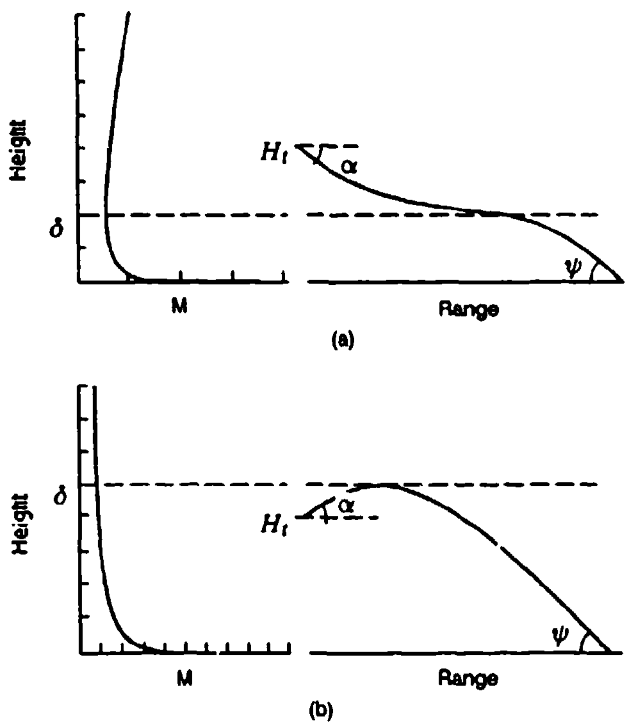

Figure 1. Ray trace for antenna (a) above the evaporation duct height and (b) below the evaporation duct height.

These calculations of the grazing angle do not take into account the effect that a surface-based duct from elevated refractive layers could have on the clutter return for a radar in the duct.

3.2 RADAR CLUTTER CROSS SECTION

Wind speed and direction and average wave height are used to describe the condition of the sea surface. Radar frequency and polarization are system parameters that, along with the grazing angle, describe the effects of the interaction between an electromagnetic wave and the sea surface. Radar wavelength, λ, is

$$\lambda = \frac{300}{f} \qquad \text{(m)} \qquad (17)$$

where f is frequency in megahertz. Average wavelength of the ocean windwaves, h_{av}, is

$$h_{av} = \left(\frac{V_w}{8.67}\right)^{2.5} \qquad \text{(m)} \qquad (18)$$

where V_w is wind speed in m/s. Equation 18 assumes a fully risen sea and steady-state conditions. Under transient conditions, V_w and h_{av} are decoupled; the model can be used with these two variables input separately. Three factors need to be calculated. The interference factor is

$$A_i = \frac{\sigma_\phi^4}{1 + \sigma_\phi^4} \qquad (19)$$

where

$$\sigma_\phi = \frac{(14.4\ \lambda + 5.5)\psi h_{av}}{\lambda} \qquad (20)$$

The upwind/downwind factor is

$$A_u = \exp[0.2\cos(\phi)(1 - 2.8\psi)(\lambda + 0.02)^{-0.4}] \qquad (21)$$

where ϕ is the wind direction (degrees) relative to the antenna boresight. The wind speed factor is

$$A_w = \left(\frac{1.9425 V_w}{1 + \frac{V_w}{15}}\right)^{q_w} \qquad (22)$$

where the exponent $q_w = 1.1\ (\lambda + 0.02)^{-0.4}$. Then, the average radar cross section per unit area for horizontal polarization is

$$\sigma_{hh}^0 = 10\log(3.9 \times 10^{-6}\lambda\psi^{0.4}A_i A_u A_w) \qquad \text{(dB)} \qquad (23)$$

where the subscript hh indicates horizontal polarization on transmit and receive. (Cross-polarization clutter levels are not considered.) For vertical polarization and frequencies of 3000 MHz and greater

$$\sigma_{vv}^0 = \sigma_{hh}^0 - 1.05\ln(h_{av} + 0.02) + 1.09\ln(\lambda) + 1.27\ln(\psi + 0.0001) + 9.7 \qquad (24)$$

(dB)

where ln is the natural logarithm. For vertical polarization and frequencies less than 3000 MHz

$$\sigma_{vv}^0 = \sigma_{hh}^0 - 1.73\ln(h_{av} + 0.02) + 3.76\ln(\lambda) + 2.46\ln(\psi + 0.0001) + 22.2 \qquad (25)$$

(dB)

For circular polarization, σ^0 is equal to the larger of σ^0_{vv} or σ^0_{hh} minus 6 dB. The clutter at the maximum range is determined by linear interpolation. If the maximum range exceeds the range for which grazing angles can be calculated, an attenuation rate is applied to the last calculated value of σ^0 at the limiting grazing angle ψ_l. The attenuation rate is adapted from the standard propagation model:[5]

$$\alpha = \{92.516 - [8608.7593 - (\Delta - 20.2663)^2]^{1/2}\} \quad \text{(dB/km)} \qquad (26)$$

where Δ is the scaled evaporation duct height, and α is constrained to be no less than 0.0009. The scaled evaporation duct height is

$$\Delta = \delta \; Z_N \qquad \text{(m)} \qquad (27)$$

which is constrained to be 23.3 meters or less. The attenuation rate is also scaled by

$$\beta = \alpha \; R_N \qquad \text{(dB/km)} \qquad (28)$$

Z_N and R_N are height and range scaling factors found from

$$\begin{aligned} Z_N &= 2.214 \;\; 10^{-3} f^{2/3} \\ R_N &= 4.705 \;\; 10^{-2} f^{1/3} \end{aligned} \qquad (29)$$

The normalized radar clutter cross section at the maximum range is then

$$\sigma_{r\,max} = \sigma^0_{\psi_l} - 2\,\beta\,\Delta r \qquad \text{(dB)} \qquad (30)$$

where Δr is the range difference between $rmax$ and the range of ψ_l. This model for normalized radar clutter cross section does not take ocean swell into account.

The clutter cross section is

$$\sigma_c = \sigma^0 + A_c \qquad \text{(dBsm)} \qquad (31)$$

where σ^0 is normalized radar cross section of the sea surface and A_c is the area of ocean surface illuminated by the radar:

$$A_c = 10 \log (1890 \; BW_h \; \tau_c \qquad \text{(dBsm)} \qquad (32)$$

where BW_h is horizontal beamwidth in degrees, τ_c is compressed pulse length in microseconds, and r is range in kilometers. If the radar does not use pulse compression techniques, then the normal pulse length in microseconds is used in determining the area of the radar resolution cell.

4.0 TEST CASES FOR CALCULATION OF AVERAGE SEA CLUTTER

This section lists input data and output data to verify the proper implementatation of the computer program listed in the appendix. Intermediate results are also included to aid in isolating errors. Table 3 lists the input data for the first test case. This test case is typical of clutter under standard propagation conditions for an X-band radar system. Table 4 shows intermediate calculations of elevation angle, grazing angle at the surface, normalized radar sea clutter, and radar resolution cell versus range. Table 5 shows the final results of sea clutter versus range. If the program is properly implemented, the final results should agree within ±1 in the least significant digit.

Table 3. Input data for Test Case 1.

Input		Description
5.0		! surface wind speed in m/s
0.0		! wind dir. rel. to boresight (deg)
0.0		! evap duct ht in m
4		! # of levels in profile
0.0	350.0	! ht. & *M* arrays in m & *M*
10.0	351.0	
1000.0	468.0	
5000.0	940.0	
30.0		! radar antenna ht (m)
9000.0		! radar freq (MHz)
H		! antenna polarization
2.5		! hor. beam width (deg)
1.0		! compressed pulse length (μs)
50.0		! max range (km)

Table 4. Intermediate results for Test Case 1.

Range, r (km)	Elevation Angle, α (rad)	Grazing Angle, ψ (rad)	Normalized Radar Sea Clutter, σ^0 (dB)	Radar Resolution Cell, A_c (dBsm)	Radar Sea Clutter, σ_c (dBsm)
0.17452	−0.17193	0.17191	−39.82479	29.16253	−10.66226
0.23234	−0.12912	0.12909	−39.98860	30.40524	−9.58336
0.34773	−0.08630	0.08626	−40.36736	32.15649	−8.21087
0.38600	−0.07774	0.07769	−40.49141	32.60989	−7.88152
0.43380	−0.06918	0.06912	−40.64383	33.11694	−7.52689
0.49523	−0.06061	0.06055	−40.83755	33.69205	−7.14550
0.57673	−0.05205	0.05198	−41.09835	34.35378	−6.74457
0.69049	−0.04349	0.04340	−41.48647	35.13559	−6.35088
0.86033	−0.03492	0.03482	−42.17085	36.09069	−6.08016
1.14118	−0.02636	0.02622	−43.71303	37.31754	−6.39549
1.69574	−0.01780	0.01759	−47.98866	39.03761	−8.95105
1.78255	−0.01694	0.01672	−48.71342	39.25444	−9.45898
1.87883	−0.01608	0.01585	−49.51404	39.48289	−10.03115
1.98618	−0.01523	0.01498	−50.39718	39.72420	−10.67298
2.10665	−0.01437	0.01411	−51.37030	39.97995	−11.39035
2.24286	−0.01352	0.01324	−52.44196	40.25204	−12.18991
2.39813	−0.01266	0.01236	−53.62233	40.54275	−13.07958
2.57681	−0.01180	0.01148	−54.92403	40.85485	−14.06919
2.78473	−0.01095	0.01060	−56.36315	41.19185	−15.17130
3.02988	−0.01009	0.00971	−57.96095	41.55827	−16.40268
3.32345	−0.00923	0.00882	−59.74651	41.95991	−17.78660
3.68186	−0.00838	0.00792	−61.76105	42.40469	−19.35636
4.13012	−0.00752	0.00701	−64.06571	42.90364	−21.16207
4.70864	−0.00667	0.00608	−66.75675	43.47298	−23.28378
5.48822	−0.00581	0.00512	−69.99928	44.13834	−25.86095
6.60798	−0.00495	0.00413	−74.11634	44.94470	−29.17164
8.39934	−0.00410	0.00305	−79.90308	45.98647	−33.91661
12.06655	−0.00324	0.00173	−90.68350	47.55985	−43.12365

Table 5. Final values for Test Case 1.

Range, r (km)	Average Radar Sea Clutter, σ_c (dBsm)
0.17	-10.66
0.23	-9.58
0.35	-8.21
0.39	-7.88
0.43	-7.53
0.50	-7.15
0.58	-6.74
0.69	-6.35
0.86	-6.08
1.14	-6.40
1.70	-8.95
1.78	-9.46
1.88	-10.03
1.99	-10.67
2.11	-11.39
2.24	-12.19
2.40	-13.08
2.58	-14.07
2.78	-15.17
3.03	-16.40
3.32	-17.79
3.68	-19.36
4.13	-21.16
4.71	-23.28
5.49	-25.86
6.61	-29.17
8.40	-33.92
12.07	-43.12
50.00	-183.45

Table 6 lists the input data for Test Case 2. This test case varies from Test Case 1 in that the relative wind is a crosswind and the propagation conditions are that of a 13-meter evaporation duct. Table 7 shows intermediate calculations of elevation angle, grazing angle at the surface, normalized radar sea clutter, and radar resolution cell versus range. Table 8 shows the final results of sea clutter versus range. If the program is properly implemented, the final results should agree within ±1 in the least significant digit.

Table 6. Input data for Test Case 2.

Input		Description
5.0		! surface wind speed in m/s
90.0		! wind dir. rel. to boresight (deg)
13.0		! evap duct ht in m
4		! # of levels in profile
0.0	350.0	! ht. & *M* arrays in m & *M*
10.0	351.0	
1000.0	468.0	
5000.0	940.0	
30.0		! radar antenna ht (m)
9000.0		! radar freq (MHz)
H		! antenna polarization
2.5		! hor. beam width (deg)
1.0		! compressed pulse length (μs)
50.0		! max range (km)

Table 7. Intermediate results for Test Case 2.

Range, r (km)	Elevation Angle, α (rad)	Grazing Angle, ψ (rad)	Normalized Radar Sea Clutter, σ^0(dB)	Radar Resolution Cell, A_c (dBsm)	Radar Sea Clutter, σ_c (dBsm)
0.17330	-0.17277	0.17286	-41.27011	29.13188	-12.13823
0.23212	-0.12949	0.12961	-41.77278	30.40117	-11.37162
0.34837	-0.08621	0.08639	-42.49220	32.16438	-10.32782
0.38675	-0.07755	0.07776	-42.68478	32.61832	-10.06646
0.43536	-0.06890	0.06913	-42.90594	33.13248	-9.77346
0.49805	-0.06024	0.06050	-43.16871	33.71676	-9.45195
0.58163	-0.05158	0.05189	-43.49904	34.39051	-9.10853
0.69889	-0.04293	0.04330	-43.95747	35.18808	-8.76938
0.87557	-0.03427	0.03473	-44.71241	36.16693	-8.54547
1.17170	-0.02562	0.02623	-46.30869	37.43217	-8.87651
1.77088	-0.01696	0.01787	-50.42794	39.22591	-11.20202
1.86633	-0.01610	0.01705	-51.09497	39.45390	-11.64107
1.97272	-0.01523	0.01624	-51.82214	39.69468	-12.12746
2.09198	-0.01436	0.01543	-52.61243	39.94959	-12.66284
2.22664	-0.01350	0.01463	-53.46852	40.22051	-13.24801
2.37983	-0.01263	0.01383	-54.39278	40.50948	-13.88329
2.55577	-0.01177	0.01305	-55.38715	40.81924	-14.56791
2.75992	-0.01090	0.01227	-56.45305	41.15298	-15.30007
2.99960	-0.01004	0.01151	-57.59114	41.51465	-16.07649
3.28506	-0.00917	0.01077	-58.80091	41.90945	-16.89146
3.63102	-0.00831	0.01004	-60.08001	42.34431	-17.73570
4.05901	-0.00744	0.00934	-61.42309	42.82822	-18.59487
4.60268	-0.00657	0.00866	-62.82013	43.37412	-19.44600
5.31701	-0.00571	0.00802	-64.25374	44.00069	-20.25305
6.29973	-0.00484	0.00743	-65.69566	44.73724	-20.95842
7.74440	-0.00398	0.00690	-67.10223	45.63390	-21.46833
10.10779	-0.00311	0.00644	-68.41035	46.79058	-21.61978
14.89990	-0.00225	0.00607	-69.53645	48.47585	-21.06060
52.84929	-0.00138	0.00581	-70.38317	53.97441	-16.40876

Table 8. Final values for Test Case 2.

Range, r (km)	Average Radar Sea Clutter, σ_c (dBsm)
0.17	-12.14
0.23	-11.37
0.35	-10.33
0.39	-10.07
0.44	-9.77
0.50	-9.45
0.58	-9.11
0.70	-8.77
0.88	-8.55
1.17	-8.88
1.77	-11.20
1.87	-11.64
1.97	-12.13
2.09	-12.66
2.23	-13.25
2.38	-13.88
2.56	-14.57
2.76	-15.30
3.00	-16.08
3.29	-16.89
3.63	-17.74
4.06	-18.59
4.60	-19.45
5.32	-20.25
6.30	-20.96
7.74	-21.47
10.11	-21.62
14.90	-21.06
50.00	-16.76

Table 9 lists the input data for Test Case 3. Test Case 3 verifies the proper operation of the program at a lower frequency under propagation conditions defined by an effective earth radius factor of 1.2 ($dM/dz = 0.13\ M$/m). Table 10 shows intermediate calculations of elevation angle, grazing angle at the surface, normalized radar sea clutter, and radar resolution cell versus range. Table 11 shows the final results of sea clutter versus range. If the program is properly implemented, the final results should agree within ± 1 in the least significant digit.

Table 9. Input data for Test Case 3.

Input		Description
5.0		! surface wind speed in m/s
0.0		! wind dir. rel. to boresight (deg)
0.0		! evap duct ht in m
3		! # of levels in profile
0.0	350.0	! ht. & *M* arrays in m & *M*
10.0	480.0	
1000.0	1000.0	
5000.0		
30.0		! radar antenna ht (m)
1000.0		! radar freq (MHz)
H		! antenna polarization
2.4		! hor. beam width (deg)
1.0		! compressed pulse length (μs)
50.0		! max range (km)

Table 10. Intermediate results for Test Case 3.

Range, r (km)	Elevation Angle, α (rad)	Grazing Angle, ψ (rad)	Normalized Radar Sea Clutter, σ^0 (dB)	Radar Resolution Cell, A_c (dBsm)	Radar Sea Clutter, σ_c (dBsm)
0.17188	-0.17453	0.17453	-47.58787	28.91886	-18.66901
0.43307	-0.06925	0.06925	-58.02119	32.93227	-25.08892
0.69426	-0.04317	0.04317	-66.57854	34.98193	-31.59661
0.95545	-0.03134	0.03134	-72.60278	36.36879	-36.23398
1.21664	-0.02458	0.02458	-77.20615	37.41834	-39.78781
1.47783	-0.02020	0.02020	-80.93079	38.26297	-42.66782
1.73902	-0.01714	0.01714	-84.06212	38.96977	-45.09235
2.00021	-0.01487	0.01487	-86.76709	39.57748	-47.18961
2.26140	-0.01312	0.01312	-89.15154	40.11050	-49.04104
2.52259	-0.01173	0.01173	-91.28673	40.58520	-50.70153
2.78378	-0.01060	0.01060	-93.22287	41.01308	-52.20979
3.04497	-0.00966	0.00966	-94.99673	41.40256	-53.59417
3.30616	-0.00886	0.00886	-96.63602	41.75997	-54.87605
3.56735	-0.00818	0.00818	-98.16217	42.09019	-56.07198
3.82854	-0.00759	0.00759	-99.59206	42.39706	-57.19499
4.08973	-0.00707	0.00707	-100.93926	42.68368	-58.25558
4.35092	-0.00661	0.00661	-102.21488	42.95255	-59.26234
4.61211	-0.00621	0.00621	-103.42805	[illegible].20573	-60.22232
4.87330	-0.00584	0.00584	-104.58645	43.44497	-61.14148
5.13449	-0.00551	0.00551	-105.69657	43.67171	-62.02486
5.39568	-0.00521	0.00521	-106.76396	43.88720	-62.87677
5.65688	-0.00494	0.00494	-107.79343	44.09249	-63.70094
5.91807	-0.00469	0.00469	-108.78914	44.28853	-64.50061
6.17926	-0.00446	0.00446	-109.75471	44.47609	-65.27863
6.44045	-0.00424	0.00424	-110.69342	44.65589	-66.03753
6.70164	-0.00404	0.00404	-111.60809	44.82854	-66.77954
6.96283	-0.00386	0.00386	-112.50133	44.99459	-67.50674
7.22402	-0.00369	0.00369	-113.37543	45.15452	-68.22092
7.48521	-0.00352	0.00352	-114.23251	45.30877	-68.92374
7.74640	-0.00337	0.00337	-115.07449	45.45773	-69.61676
8.00759	-0.00323	0.00323	-115.90313	45.60175	-70.30138
8.26878	-0.00309	0.00309	-116.72008	45.74115	-70.97893
8.52997	-0.00297	0.00297	-117.52682	45.87621	-71.65061
8.79116	-0.00284	0.00284	-118.32481	46.00719	-72.31762
9.05235	-0.00273	0.00273	-119.11538	46.13435	-72.98103
9.31354	-0.00262	0.00262	-119.89980	46.25788	-73.64191
9.57473	-0.00251	0.00251	-120.67928	46.37800	-74.30128
9.83592	-0.00241	0.00241	-121.45501	46.49488	-74.96013
10.09711	-0.00232	0.00232	-122.22810	46.60870	-75.61940
10.35830	-0.00223	0.00223	-122.99966	46.71962	-76.28004
10.61950	-0.00214	0.00214	-123.77080	46.82777	-76.94302
10.88069	-0.00205	0.00205	-124.54256	46.93330	-77.60926
11.14188	-0.00197	0.00197	-125.31601	47.03632	-78.27969
11.40307	-0.00189	0.00189	-126.09224	47.13695	-78.95529
11.92545	-0.00175	0.00175	-127.65739	[illegible]7.33148	-80.32591

Table 11. Final values for Test Case 3.

Range, r (km)	Average Radar Sea Clutter, σ_c (dBsm)
0.17	-18.67
0.43	-25.09
0.69	-31.60
0.96	-36.23
1.22	-39.79
1.48	-42.67
1.74	-45.09
2.00	-47.19
2.26	-49.04
2.52	-50.70
2.78	-52.21
3.04	-53.59
3.31	-54.88
3.57	-56.07
3.83	-57.19
4.09	-58.26
4.35	-59.26
4.61	-60.22
4.87	-61.14
5.13	-62.02
5.40	-62.88
5.66	-63.70
5.92	-64.50
6.18	-65.28
6.44	-66.04
6.70	-66.78
6.96	-67.51
7.22	-68.22
7.49	-68.92
7.75	-69.62
8.01	-70.30
8.27	-70.98
8.53	-71.65
8.79	-72.32
9.05	-72.98
9.31	-73.64
9.57	-74.30
9.84	-74.96
10.10	-75.62
10.36	-76.28
10.62	-76.94
10.88	-77.61
11.14	-78.28
11.40	-78.96
11.93	-80.33
50.00	-144.79

Table 12 lists the input data for Test Case 4. Test Case 4 tests the program for a higher antenna height, vertical polarization, a wider horizontal beam, and a longer compressed pulse. Because of the

higher antenna, the maximum range has been set to 200 km. Table 13 shows intermediate calculations of elevation angle, grazing angle at the surface, normalized radar sea clutter, and radar resolution cell versus range. Table 14 shows the final results of sea clutter versus range. If the program is properly implemented, the final results should agree within ±1 in the least significant digit.

Table 12. Input data for Test Case 4.

Input		Description
5.0		! surface wind speed in m/s
0.0		! wind dir. rel. to boresight (deg)
0.0		! evap duct ht in m
4		! # of levels in profile
0.0	350.0	! ht. & *M* arrays in m & *M*
10.0	351.0	
1000.0	468.0	
5000.0	940.0	
1000.0		! radar antenna ht (m)
9000.0		! radar freq (MHz)
V		! antenna polarization
5.0		! hor. beam width (deg)
2.5		! compressed pulse length (μs)
200.0		! max range (km)

Table 13. Intermediate results for Test Case 4.

Range, r (km)	Elevation Angle, α (rad)	Grazing Angle, ψ (rad)	Normalized Radar Sea Clutter, σ^0 (dB)	Radar Resolution Cell, A_c (dBsm)	Radar Sea Clutter, σ_c (dBsm)
6.01684	-0.16655	0.16584	-34.76330	50.55831	15.79501
7.91571	-0.12680	0.12586	-35.28127	51.74952	16.46825
11.57980	-0.08704	0.08567	-36.13678	53.40163	17.26485
12.76520	-0.07909	0.07758	-36.38067	53.82490	17.44423
14.22467	-0.07114	0.06946	-36.66499	54.29504	17.63005
16.06660	-0.06319	0.06129	-37.00522	54.82386	17.81864
18.46782	-0.05524	0.05305	-37.42987	55.42878	17.[illegible]891
21.73692	-0.04729	0.04471	-38.00035	56.13660	18.13626
26.47287	-0.03934	0.03620	-38.87930	56.99263	18.11333
34.04010	-0.03139	0.02736	-40.62358	58.08453	17.46095
48.62500	-0.02344	0.01768	-45.67751	59.63322	13.95571
50.93113	-0.02264	0.01661	-46.65054	59.83446	13.18392
53.51353	-0.02184	0.01551	-47.77897	60.04926	12.27029
56.43565	-0.02105	0.01436	-49.09777	60.28016	11.18238
59.78544	-0.02025	0.01317	-50.65598	60.53058	9.87460
63.69080	-0.01946	0.01191	-52.52724	60.80539	8.27815
68.34922	-0.01866	0.01056	-54.83195	61.11196	6.28001
74.09347	-0.01787	0.00909	-57.79104	61.46242	3.67138
81.56604	-0.01707	0.00740	-61.88675	61.87971	-0.00704
92.36490	-0.01628	0.00532	-68.56870	62.41969	-6.14901
115.43026	-0.01548	0.00173	-91.32991	63.38782	-27.94209

Table 14. Final values for Test Case 4.

Range, r (km)	Average Radar Sea Clutter, σ_c (dBsm)
6.0	15.8
7.9	16.5
11.6	17.3
12.8	17.4
14.2	17.6
16.1	17.8
18.5	18.0
21.7	18.1
26.5	18.1
34.0	17.5
48.6	14.0
50.9	13.2
53.5	12.3
56.4	11.2
59.8	9.9
63.7	8.3
68.4	6.3
74.1	3.7
81.6	0.0
92.4	−6.2
115.4	−27.9
200.0	−352.2

5.0 REFERENCES

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4. Patterson, W. L., et al., "Engineer's Refractive F''ects Prediction System (EREPS) Revision 2.0," Naval Ocean Systems Center TD 1342 Revision 2.0, February 1990.

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Appendix

FORTRAN PROGRAM TO CALCULATE AVERAGE RADAR CLUTTER CROSS SECTION OF THE SEA

```
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c
c
c
c  Name:
c
c       PROGRAM MAIN
c
c  Purpose:
c
c       This program generates values of average radar clutter cross
c       section of the sea (dB) versus range (km).
c
c  Inputs:
c
c       cpl, delta, freq, hbw, height(*), Ht, imax, levels, Munits(*),
c       phi, polar, r(*), rmax, sigmac(*), Vw
c
c  Outputs:
c
c       r(*), sigmac(*)
c
c  Routines called:
c
c       clutr, system
c
c  Glossary:
c
c       cpl        - compressed pulse length (us)
c       delta      - evaporation duct height (0 to 40 m)
c       freq       - radar frequency (100 to 20000 MHz)
c       hbw        - radar horizontal beamwidth (deg)
c       height(*)  - array of height values for M-profile (m)
c       Ht         - radar antenna height (m)
c       imax       - number of elements in r and sigmac arrays
c       levels     - number of elements in height & Munits arrays
c       Munits(*)  - array of M-values (M)
c       phi        - surface wind direction relative to antenna
c                    boresight (0 to 180 deg)
c       polar      - antenna polarization
c                       H - horizontal
```

```
c                          V - vertical
c                          C - circular
c        r(*)       - array of range values (km)
c        rmax       - maximum range (km)
c        sigmac(*) - array of average sea rcs (dB)
c        Vw         - wind speed (m/s)
c
c  Method:
c
c        Input data are read from text files and passed to the clutter
c        subroutine for calculations.  Average radar clutter cross
c        section versus range is returned and printed out.  Prompts
c        for file names are written to 'stderr' and output is written
c        to 'stdout' to facilitate redirection of output.
c
c
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c
c
c
      PROGRAM MAIN
c
c
      DIMENSION height(30), sigmac(50), r(50)
      REAL * 4 Munits(30)
c
      CHARACTER * 12 filnam
      CHARACTER * 1 polar
      INTEGER * 2 levels
c
      COMMON /ENVIN/ Vw, phi, delta, levels, height, Munits
      COMMON /SYSIN/ Ht, freq, polar, hbw, cpl, rmax
c
      CALL SYSTEM ('ls E* 1>&2'//char(0))
      WRITE (7,'(//,"Enter input environment file name")')
      READ (5,'(a12)') filnam
      OPEN (10,FILE=filnam)
c
      READ (10, '(f4.1)') Vw                ! surface wind speed (m/s)
        READ  (10,  '(f3.0)')  phi                  !  wind  dir.  rel.  to
boresight
      READ (10, '(f3.0)') delta             ! evap duct ht (m)
      READ (10, '(i2)') levels
      DO i=1, levels
         READ (10, '(2f10.1)') height(i), Munits(i) ! ht & m-units
      END DO
      CLOSE (10)
c
      CALL SYSTEM ('ls S* 1>&2'//char(0))
      WRITE (7,'(//,"Enter input system file name")')
```

```
      READ (5,'(a12)') filnam
      OPEN (10,FILE=filnam)
c
      READ (10, '(f10.1)') Ht              ! radar antenna ht (m)
      READ (10, '(f10.1)') freq            ! radar freq (MHz)
      READ (10, '(a1)') polar              ! antenna polarization
      READ (10, '(f10.1)') hbw             ! hor. beam width (deg)
      READ (10, '(f10.1)') cpl             ! compr. pulse length (us)
      READ (10, '(f4.0)') rmax             ! max range (km)
      CLOSE(10)
c
      CALL clutr (sigmac, r, imax)
c
c
      DO i = 1, imax
         WRITE (6, '(2f10.2)') r(i), sigmac(i)
      END DO
c
      STOP
      END

cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c
c
c
c  Name:
c
c       SUBROUTINE clutr (sigmac, r, imax)
c
c  Purpose:
c
c       Calculates average radar cross section of the sea versus
c          range.
c
c  Inputs:
c
c       alpha(*), cpl, delta, freq, hbw, imax, psi(*), r(*),
c       rmax, sigma0(*)
c
c  Outputs:
c
c       sigmac(*), r(*)
c
c  Calling routines:
c
c       MAIN
c
c  Routines called:
c
c       ALOG10, FLOAT, getk, IFIX, mprof, nrcs, psir, psirae, SQRT
```

```
c
c  Glossary:
c
c       alpha(*)     - depression angle array, deg.
c       cpl          - radar receiver compressed pulse length, microsec
c       delta        - evaporation duct height, 0 - 40 meters
c       freq         - radar system frequency, 100 - 20000 MHz
c       hbw          - radar antenna horizontal beam width, deg
c       imax         - number of elements in sigmac array
c       psi(*)       - grazing angle array
c       r(*)         - range array corresponding to sigmac (km)
c       rmax         - maximum range, km
c       sigmac(*)    - average radar cross section of the sea dB
c       sigma0(*)    - normalized radar reflectivity of the sea surface,
c                      sq. meters per sq. meter
c
c  Method:
c
c            A grazing angle model is selected, depending upon
c            frequency, to determine grazing angle versus range. These
c            grazing angles are input to the routine that calculates
c            normalized sea clutter cross section. Normalized clutter
c            is converted to average clutter by multiplying by the
c            radar's clutter resolution cell at each range. Beyond
c            the range of the minimum grazing angle, an attenuation
c            rate dependent upon evaporation duct conditions is applied
c            to the sea surface reflectivity calculated at the range of
c            the minimum grazing angle.
c

c
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c
c
c
      SUBROUTINE  clutr (sigmac, r, imax)
c
      DIMENSION height(30)
      REAL * 4  Munits(30)
      DIMENSION alpha(50), psi(50), r(50), sigma0(50), sigmac(50)
      DIMENSION dMdh(32), hmrs(32)
c
      CHARACTER * 1 polar
      INTEGER * 2 levels
c
      COMMON /ENVIN/ Vw, phi, delta, levels, height, Munits
      COMMON /SYSIN/ Ht, freq, polar, hbw, cpl, rmax
c
c           If freq >= 2 GHz, then evaporation duct effects dominate
c        determination of grazing angle.  If freq < 2 GHz, then
```

```
c        effective earth radius effects are assumed to dominate the
c        determination of grazing angle.
c
      IF (freq .GE. 2000.) THEN
         CALL psir(delta, Ht, alpha, psi, r, imax)
      ELSE
         CALL mprof (height, Munits, Ht, levels, ALPHAC, DMDH, HMRS,
     2               SBDHT, NTOT)
         CALL getk (alphac, dMdh, hmrs, ntot, Ht, RK)
         CALL psirae (rk, Ht, rmax, alpha, psi, r, imax)
      END IF
c
c             invert r, psi, and alpha arrays so range increases with
index
c
      limit= IFIX(FLOAT(imax)/2.)
      DO i=1, limit
         rng = r(i)
         angle = alpha(i)
         angl = psi(i)
         r(i) = r(imax+1-i)
         psi(i) = psi(imax+1-i)
         alpha(i) = alpha(imax+1-i)
         r(imax+1-i) = rng
         psi(imax+1-i) = angl
         alpha(imax+1-i) = angle
      END DO
c
c          determine reflectivity from grazing angle
c
      DO i = 1, imax
         CALL nrcs (Vw, phi, freq, polar, psi(i), sigma0(i))
      END DO
c
c          calculate average clutter cross section from normalized
c          reflectivity and clutter resolution cell size
c
      acs = 10.*ALOG10(1890.*hbw*cpl)
      DO i = 1, imax
         ac = acs + 10.*ALOG10(r(i))
         sigmac(i) = sigma0(i) + ac
         write (6,'(6f12.5)') r(i), alpha(i), psi(i), sigma0(i), ac,
     2                        sigmac(i)
      END DO
c
c          beyond minimum grazing angle, apply an attenuation rate
c          to the reflectivity
c
      IF (r(imax) .LT. rmax) THEN
         reflim = sigma0(imax)
```

```
         rlim = r(imax)
         zfac = (freq/9600.)**(2./3.)
         rfac = (freq/9600.)**(1./3.)
         del = delta * zfac
         IF (del .GT. 23.3)  del = 23.3
         atten = 92.516 - SQRT(8608.7593-(del-20.2663)**2)
         IF (atten .LT. 0.0009)  atten = 0.0009
         atten = atten * rfac
         sigma = reflim - 2. * atten * (rmax - rlim)
         ac = acs + 10.*ALOG10(rmax)
         imax = imax + 1
         r(imax) = rmax
         sigmac(imax) = sigma + ac
      ELSE IF (r(imax) .GT. rmax) THEN
c
c              use linear interpolation to find sigma_c at rmax
c
         i = 1
         DO WHILE (rmax .GT. r(i))
            i = i + 1
         END DO
         dr = (rmax-r(i-1)) / (r(i)-r(i-1))
         ds = sigmac(i) - sigmac(i-1)
         temp = ds * dr + sigmac(i-1)
         imax = i
         r(imax) = rmax
         sigmac(imax) = temp
      END IF
c
      RETURN
      END



cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c
c
c  Name:
c
c        SUBROUTINE downgo (alpha, ixmtr, r)
c
c  Purpose:
c
c        Ray trace for downgoing rays, alpha < 0
c
c  Inputs:
c
c        alpha, rhl(*), rml(*), ixmtr
c
```

```
c  Outputs:
c
c       r
c
c  Calling routines:
c
c       psir
c
c  Routines called:
c
c       SQRT
c
c  Glossary:
c
c       alpha   - launch angle in radians
c       ixmtr   - index of level in profile for transmitter
c       rhl(*)  - height (m)
c       rml(*)  - modified refractivity (M)
c       r       - range (km)
c
c  Method:
c
c          A downgoing ray is traced through the successive layers of
c       the M profile to determine the range at which it strikes the
c       surface.
c
c
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c
c
      SUBROUTINE downgo (alpha, ixmtr, r)
c
      DIMENSION rhl(10), rml(10)
c
      COMMON /RAYTRACE/ rhl, rml
c
       i = ixmtr
       DO WHILE (i .GT. 1)
          dh = rhl(i) - rhl(i-1)
          dm = rml(i) - rml(i-1)
          dmdh = dm/dh
          IF (dmdh .EQ. 0.) dmdh = 1e-8
          alphap = -SQRT(alpha**2 + 0.000002*dmdh*(rhl(i-1)-rhl(i)))
          rp = r + (alphap-alpha)/(dmdh*0.001)
          alpha = alphap
          r = rp
          i = i - 1
       END DO
c
      RETURN
```

```
      END
c
c  Subroutine ducts
c
c  DUCTS builds an array containing the top, bottom, and
c  minimum refractivity of all the major ducts in the
c  atmosphere refractivity profile.
c
c  Variable:        Description:
c    dct          3,*  duct parameters array.
c                   1,n  bottom of duct 'n', meters.
c                   2,n  top of duct 'n', meters.
c                   3,n  minimum refractivity of duct 'n', M-units.
c    lvls         Number of refractivity level in rmu, rhts.
c    ndcts        in:  the maximum number of ducts allowed.
c                 out: the number of ducts found.
c    nq           Duct counter.
c    rht          Height array, meters.
c    rmu          Modified refractivity, M-unit array, elements
c                   correspond to like-number elements of rht array.
c
c
      SUBROUTINE ducts(rmu,rht,lvls,DCT,NDCTS)
c
      real*4 dct,delu,delh,deltu,hbot,htop,rht(32),rmu(32)
      integer*2 lvls,ibot,iduct,iend,iq,itop,ndcts,nq
      dimension dct(3,8)
c
c       Locate all major ducts
      nq=0
      iq=3*ndcts
      itop=lvls
      iend=ndcts
      ndcts=0
      DO iduct=1,iend
c
c          Look for top of next duct
 1010     continue
          htop=rht(itop)
          if(itop.eq.1) go to 1060
          ibot=itop-1
          if(rmu(itop).le.rmu(ibot)) go to 1020
          itop=itop-1
          go to 1010
c
c          Look for bottom of the duct
 1020     continue
          hbot=rht(ibot)
          if(rmu(ibot).lt.rmu(itop)) go to 1030
          if(ibot.eq.1) go to 1040
```

```
        ibot=ibot-1
        go to 1020
c
c         Calculate bottom of duct using linear interpolation
 1030   continue
        delu=rmu(ibot+1)-rmu(ibot)
        delh=rht(ibot+1)-rht(ibot)
        deltu=rmu(itop)-rmu(ibot)
        if(delu.lt.0.01) go to 1040
        hbot=rht(ibot) + deltu*delh/delu
c
c         Store duct parameters in array dct
 1040   continue
        amu=rmu(itop)
        call push(dct,iq,nq,amu)
        call push(dct,iq,nq,htop)
        call push(dct,iq,nq,hbot)
        ndcts=iduct
        itop=ibot
     END DO
c
 1060 continue
     RETURN
     END
c
c  Subroutine getk
c
c  Subroutine GETK is used to determine the effective earth radius
c  factor k.  Getk accomplishes this by tracing a ray from the trans-
c  mitter height to 200 NMi (370 km).  The ray launch angle is 0 deg.
c  if no surface-based duct exists, or alphac, the critical angle if
c  one does.
c
c  Variable:        Description:
c    alphac       Critical angle necessary to escape duct.  If alphac
c                   = 0 then no surface-based duct exists.
c    a0           Initial ray launch angle, radians.
c    a1           Ray angle at top of layer, radians.
c    deld         Range difference, km.
c    delh         Height difference, meters.
c    delM         M-unit difference.
c    delmdh       M-unit gradient.
c    dMdh         M-unit gradient array.
c    hlast        Height at 370 km.
c    hmrs         Array of height elements, in meters.
c    ntot         Maximum number of elements in hmrs and dMdh arrays.
c    rdeld        Range incremented in ray trace.
c    rmax         Maximum range for ray trace - 370 km.
c    rng          Range, km.
c    rk           Effective earth radius factor.
```

```
c    xmtr        Transmitter height in meters.
c
     SUBROUTINE getk(alphac, dMdh, hmrs, ntot, xmtr, RK)
c
     real*4 alphac, a0, a1, deld, delh, delM, delmdh, dMdh(32)
     real*4 hlast, hmrs(32), rdeld, rmax, rng, rk, xmtr
     integer*2 ntot, i
c
     rmax = 370.0
     h = xmtr
     rng = 0.0
     a0 = alphac
c       Loop to trace ray through the atmospheric layers.
     DO i=2,ntot-1
       delm = (hmrs(i+1) - h)*dMdh(i)*1.0E-3
       a1 = SQRT(a0*a0 + 2.0*delm)
       deld = (a1 -a0)/dMdh(i)
       rdeld = rng + deld
       IF(rdeld .GT. rmax) GOTO 1000
       a0 = a1
       h = hmrs(i+1)
       rng = rdeld
     END DO
     i = ntot
1000 continue
c      Ray trace in final layer to range rmax.
     deld = rmax - rng
     a1 = a0 + dMdh(i) * deld
     delM = (a1*a1 - a0*a0)*0.5
     delh = 1000.0*delM/dMdh(i)
     hlast = hmrs(i) + delh
c      Determine the equivalent single-gradient atmosphere that
c      would be required to trace a ray launched at alphac that
c      would arrive at height = hlast at a range of 370 km.
     delmdh = (-alphac)*2.0/rmax + 2.0E-3*(hlast - xmtr)/(rmax*rmax)
     rk = 1.0/(6371.0 * delmdh)
     IF(rk .GT. 5.0) rk = 5.0
     IF(rk .LE. 0.5) rk = 0.50
     RETURN
     END
c
c  Subroutine insrt
c
c
c  INSRT inserts (or appends) a new level into the M-unit profile.  It
c  does this by locating the  new height relative to the existing pro-
c  file heights.  If the new height is greater than the top level, then
c  append a new level for the new height.  If the new height is between
c  two levels, then insert a new level for the new height.  If the new
c  height is equal to an existing level's height, do not add a new
```

```
c  level for the new height.
c
c  Variable:        Description:
c    amu          Modified refractivity array, M-units.
c    hmrs         Height array, meters, each element corresponding to
c                   the like-number amu array element.
c    iq           Number of levels in amu and hmrs.
c    hgt          Height of new level to be added, meters.
c    ipnt         Index pointer to new level.
c
c
      SUBROUTINE insrt(amu,hmrs,iq,hgt,ipnt)
c
      real*4 amu(32),hmrs(32),hgt
      integer*2 iq,ipnt
c
      DO i=1,iq
         ilevel=i
         IF(ABS(hgt-hmrs(ilevel)).LE.0.01) go to 1020
         IF(hmrs(ilevel).GT.hgt) go to 1030
      END DO
c
c       Hgt > amu(iq)
      iq=iq+1
      ipnt=iq
      grdnt=0.1181102
      amu(ipnt)=amu(iq-1) + (hgt-hmrs(iq-1))*grdnt
      hmrs(ipnt)=hgt
      go to 1050
c
c       Hgt = hmrs(ilevel)
 1020 continue
      ipnt=ilevel
c     amu(ipnt)=amu(ilevel)
      hmrs(ipnt)=hgt
      go to 1050
c
c       Hmrs(ilevel) > hgt > hmrs(ilevel-1)
 1030 continue
c       Shift levels above new height up one
      DO i=ilevel,iq
         j=iq - (i-ilevel)
         hmrs(j+1)=hmrs(j)
         amu(j+1)=amu(j)
      END DO
      iq=iq+1
      ipnt=ilevel
      grdnt=(amu(ipnt+1)-amu(ipnt-1))/(hmrs(ipnt+1)-hmrs(ipnt-1))
      amu(ipnt)=amu(ipnt-1) + (hgt-hmrs(ipnt-1))*grdnt
      hmrs(ipnt)=hgt
```

```
c     go to 1050
c
 1050 continue
      RETURN
      END
c
c  Subroutine mprof
c
c  MPROF modifies the M-unit and height arrays  by inserting a level at
c  the antenna height using straight line interpolation (or a standard
c  atmosphere gradient) to calculate its M-unit value.  The new profile
c  is then used to locate any ducts that might be contained in the pro-
c  file.  If the bottom of the duct is below the EM system antenna
c  height, and the top above the antenna height, then a critical angle
c  is calculated for the EM system in the surface-based duct.  (It is
c   assumed that low-elevated ducts are surface ducts if the EM system
is
c   in the duct.)
c
c  Variable:         Description:
c     alphac          The critical penetration angle necessary to escape
duct
c    amu          An array of M-unit values
c    antena       EM system antenna height
c    antmu        M-unit value at the EM system antenna height
c    dcts         24  duct parameter array
c                     1,n  bottom of duct 'n', meters
c                     2,n  top of duct 'n', meters
c                     3,n  minimum refractivity of duct 'n', m-units
c    dMdh         M-unit gradient array
c    hbot         Height of the bottom of a duct
c    htop         Height of the top of a duct
c    height       Height array with the original profile heights
c    hmrs         Height array with elements corresponding to the dMdh
c                   array elements
c    lvlant       EM system antenna level
c    lvltop       Maximum number of layers in the hmrs array
c    Munits       M-unit array with elements corresponding to the height
c                   array elements
c    ndcts        The number of ducts stored in 'dcts'
c    nmax         The number of elements in the height and Munit arrays
c    ntot         The number of elements in the dMdh and hmrs arrays
c    rma          M-unit value at the minimum on the duct profile
c    sbdht        The height of the surface-based duct
c
c    Variables not listed are temporary variables.
c
c
      SUBROUTINE mprof(height,Munits,antena,nmax,ALPHAC,DMDH,HMRS,
     1                     SBDHT,NTOT)
```

```
c
c
      real*4 alphac,amu(32),antena,dmdh(32),hmrs(32),height(30)
      real*4 Munits(30),sbdht
      real*4 antmu,dcts,hb,ht,rma
      integer*2 lvlant,lvltop,nmax,ntot
      integer*2 ndcts
      dimension dcts(3,8)
c
      lvltop = nmax
      alphac = 0.0
      sbdht = 0.0
c
c       Copy height and m-unit arrays.
c
      lvltop = nmax
      DO i = 1, nmax
         hmrs(i)=height(i)
         amu(i)=Munits(i)
      END DO
c
c       Insert new level at the antenna height.
c
      call insrt(amu,hmrs,lvltop,antena,lvlant)
      antmu=amu(lvlant)
c
c       Locate all major ducts.
      ndcts=8
      call ducts(amu,hmrs,lvltop,dcts,ndcts)
c
c       Define trapping duct parameters.
      IF(ndcts .NE. 0)THEN
        DO iduct=1,ndcts
          hb=dcts(1,iduct)
          ht=dcts(2,iduct)
          rma=dcts(3,iduct)
          IF((antena .GT. hb) .AND. (antena .LT. ht)) go to 1040
          IF(hb.lt.0.01) go to 1040
        END DO
      END IF
c
c       Antenna not inside a major duct.
      go to 1050
c
c       The antenna is inside a low-level elevated duct
c          or inside a surface-based duct.
 1040    continue
      sbdht = ht
      alphac=1.0e-3*sqrt(2.0*(antmu-rma)) + 1.0e-5
 1050 continue
```

```
c
c     Delete all levels between the surface and the antenna level.
      DO i = lvlant,lvltop
         j=i-(lvlant-2)
         hmrs(j)=hmrs(i)
         amu(j)=amu(i)
      END DO
      lvltop=j
      lvlant=2
c
c       Calculate the M-unit gradient array.
      iend=lvltop-1
      DO i = 1, iend
         delu=amu(i+1)-amu(i)
         delh=hmrs(i+1)-hmrs(i)
         dmdh(i)=1.0e-3*delu/delh
      END DO
      dmdh(lvltop)=0.1181102e-3
c
      ntot = lvltop
      RETURN
      END

ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c
c
c  Name:
c
c       SUBROUTINE nrcs (vw, phi, freq, polar, psi, sigma0)
c
c  Purpose:
c
c       Calculates the average radar clutter cross section per unit
c       area of the sea in sq. m. per sq. m.
c
c  Inputs:
c
c       freq, phi, polar, psi, vw
c
c  Outputs:
c
c       sigma0
c
c  Calling routines:
c
c       clutr
c
c  Routines called:
c
c       ALOG, ALOG10, AMAX1, COS, EXP
```

```
c
c  Glossary:
c
c       freq     - frequency (MHz)
c       phi      - angle between antenna boresight and upwind
c                  (0 to 180 deg)
c       polar    - antenna polarization
c                     H - horizontal
c                     V - vertical
c                     C - circular
c       psi      - grazing angle (radians)
c       sigma0   - normalized radar cross section of the sea (dB)
c       vw       - wind speed (m/s)
c
c  Method:
c
c       The average radar cross section per unit area (reflectivity)
c       of the sea is calculated from a deterministic parametric model
c       developed by Georgia Institute of Technology: "Radar sea
c       clutter model," Proc. IEEE International Conference on
c       Antennas and Propagation, London, Nov. 78, pp 6-10, by Horst,
c       Dyer, & Tuley.  The correction for circular polarization
c       is made in accordance with Nathanason, Radar Design Principles,
c       p. 239.   Wind and sea direction and wind speed and wave
c       height are assumed to be highly correlated; if this is not
c       a valid assumption, this code can be modified to accept
c       wind speed and average wave height as separate entrys.
c
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c
c
      SUBROUTINE nrcs (vw, phi, freq, polar, psi, sigma0)
c
      CHARACTER*1 polar
c
c
c              constants for clutter
c
        rlamda = 300. / freq                ! radar wavelength
        hav = (vw / 8.67)**2.5              ! average wave height
        cosphi = COS(phi/57.3)              ! cos of wind direction
c
c                    interference factor, ai
c
        sigma_phi = (14.4 * rlamda + 5.5) * psi * hav / rlamda
        sp4=sigma_phi**4
        ai = sp4 / (1. + sp4)
c
c                    upwind/downwind factor, au
c
```

```
        rl4 = (rlamda + 0.02)**(-0.4)
        au = EXP(0.2 * cosphi * (1. - 2.8*psi) * rl4)
c
c                       wind speed factor, aw
c
        qw = 1.1 * rl4
        aw = (1.9425 * vw / (1. + vw / 15.))**qw
c
c                       average radar cross section per unit area
c                       for horizontal polarization, sigma_hh
c
        cltr = 0.0000039 * rlamda * psi**0.4 * ai * au * aw
        sigma_hh = 10. * ALOG10(cltr)
        sigma0 = sigma_hh
c
c                        correction factor for vertical polarization
c
        IF ((polar .EQ. "V") .OR. (polar .EQ. "C")) THEN
          IF (freq .GE. 3000.) THEN
                         sigma_vv  =  sigma_hh  -  1.05*ALOG(hav+0.02)  +
1.09*ALOG(rlamda)
           sigma_vv = sigma_vv + 1.27*ALOG(psi+0.0001) + 9.7
          ELSE
                         sigma_vv  =  sigma_hh  -  1.73*ALOG(hav+0.02)  +
3.76*ALOG(rlamda)
           sigma_vv = sigma_vv + 2.46*ALOG(psi+0.0001) + 22.2
          END IF
c
c                        correction factor for circular polarization
c
          IF (polar .EQ. "C") THEN
             sigma0 = AMAX1(sigma_hh,sigma_vv) - 6
          ELSE
             sigma0 = sigma_vv
          END IF
        END IF
c
c
      RETURN
      END

cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c
c
c
c  Name:
c
c      SUBROUTINE psir (delta, hxmtr, alpha, psi, r, imax)
c
c  Purpose:
```

```
c
c      This subroutine generates arrays of ray launch angle, alpha,
c      grazing angle, psi, and  range, r, to be used as inputs to the
c      clutter level calculations.
c
c  Inputs:
c
c      delta, hxmtr
c
c  Outputs:
c
c      alpha(*), angle, idelta, imax, ixmtr, nmax1, psi(*), r(*),
c      rh1(*), rm1(*)
c
c  Calling routines:
c
c      clutr
c
c  Routines called:
c
c      ALOG, downgo, EXP, FLOAT, SQRT, upgo
c
c  Glossary:
c
c      alpha(*) - ray launch angle at the transmitter (radians)
c      angle    - ray launch angle at the transmitter (radians)
c      delta    - evaporation duct height (m)
c      hxmtr    - height of the transmitter (m)
c      idelta   - index of level in profile for delta
c      ixmtr    - index of level in profile for hxmtr
c      imax     - number of elements in alpha, psi and r arrays
c      nmax1    - number of elements in generated height and M arrays
c                     (includes radar height and evap duct profile)
c      psi(*)   - grazing angle at the sea surface (radians)
c      rh1(*)   - augmented height array (m)
c      rm1(*)   - augmented modified refractivity array (M)
c      r        - range (km)
c
c  Method:
c
c      This subroutine takes the evaporation duct height
c      and radar antenna height, and, using ray trace techniques,
c      returns grazing angle, psi (radians), as a function of range,
c      r (m).  Psi is determined directly, by Snell's law, given the
c      radar antenna height, depression (or elevation) angle at the
c      radar, the M-value at that height, and the M-value at the
c      surface.  The range is determined by using small angle
c      approximations, a linearly segmented M-profile, and analytic
c      expressions for the ray path in each segment.  The evaporation
c      duct profile is assumed to be for neutral conditions and uses
```

```
c       the Jeske formulation.  The evaporation duct profile is
c       extended to the radar antenna height, if necessary, by
c       extrapolating with a gradient of 118 M/km.
c
c
ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c
c
c
      SUBROUTINE psir (delta, hxmtr, alpha, psi, r, imax)
c
      DIMENSION  rhl(10), rml(10)
      DIMENSION alpha(50), psi(50), r(50)
c
      COMMON /RAYTRACE/ rhl, rml
c
      z0 = 0.00015       ! surface roughness parameter (m)
      zl = 6.            ! reference height (m)
      k = 0.4            ! von Karmen's constant
c
c          calculate M-profile for input delta, neutral stability
c
      rmsfc = 340.0
      rhl(1) = 0.
      rml(1) = rmsfc
       DO i = 2, 8                                        ! logarithmic
height
         rlz = FLOAT(i-4)
                     z   =   EXP(rlz)                             !   z=
0.135,0.368,1.0,2.7,7.4,20.1,54.6
         rhl(i) = z
         rml(i) = rmsfc + 0.125*z - 0.125 * Delta * ALOG(z/z0)
      END DO
      nmaxl = 8
c
c              insert delta into M-profile
c
      i = 1
      DO WHILE (rhl(i) .LT. Delta)
         i = i + 1
      END DO
      nl = i
      IF (delta .NE. rhl(i)) THEN
         nmaxl = nmaxl + 1
         DO i = nmaxl,nl+1,-1
            rhl(I) = rhl(I - 1)
            rml(I) = rml(I - 1)
         END DO
         rhl(nl) = delta
         rml(nl) = rmsfc + 0.125*delta - 0.125*delta*ALOG(delta/z0)
```

```
      END IF
      idelta = nl
      rmmin = rml(nl)
c
c           insert xmtr level into Hl & Ml arrays
c
      IF (hxmtr .GT. rhl(nmaxl)) THEN
         nmaxl = nmaxl + 1
         nl = nmaxl
         rhl(nmaxl) = hxmtr
         rml(nmaxl) = 0.118*(rhl(nmaxl)-rhl(nmaxl-1)) + rml(nmaxl-1)
         rmxmtr = rml(nmaxl)
      ELSEIF (hxmtr .EQ. rhl(nmaxl)) THEN
         rmxmtr = rml(nmaxl)
         nl = nmaxl
      ELSE
         i = 2
         DO WHILE (rhl(i) .LT. hxmtr)
            i = i + 1
         END DO
         nl = i
         IF (hxmtr .EQ. rhl(i)) THEN
            rmxmtr = rml(i)
         ELSE
            grad = (rml(i)-rml(i-1)) / (rhl(i) - rhl(i-1))
            rmxmtr = rml(i-1) + (hxmtr-rhl(i-1))*grad
            nmaxl = nmaxl + 1
            DO i = nmaxl, nl+1, -1
              rhl(i) = rhl(i-1)
              rml(i) = rml(i-1)
            END DO
            rhl(nl) = hxmtr
            rml(nl) = rmxmtr
         END IF
      END IF
      ixmtr = nl
      IF (hxmtr .LT. delta) idelta = idelta + 1
c
c           Determine psi for -10 < alpha < alphmx deg.
c           Alpha is the launch angle at the radar; alphmx is
c           the angle that yields the longest range to the surface;
c           Alphmn is max depression angle - giving a max grazing
c           angle at the surface of approx. 10 deg.
c
      alphmn = -0.1745
      radcnd = 0.000002*(rmxmtr-rmmin)
      IF (radcnd .LE. 0.) THEN
         alphmx = -0.000001
      ELSE
         alphmx = -SQRT(radcnd) - 0.000001
```

```
      END IF
      psimin = SQRT(alphmx**2 - 0.000002*(rmxmtr-rmsfc))
      IF (psimin .lt. 0.001745) THEN
         alphmx = -SQRT(0.000003+ 0.000002*(rmxmtr-rmsfc))
      END IF
      IF (hxmtr .LT. delta)  alphmx = -alphmx
      dalpha = (alphmx-alphmn) / 200.
      i = 0
      angle = alphmx
c
c           Use a variable angle decrement with smaller steps at the
c           larger ray launch angles.
c
      DO WHILE (angle .GT. alphmn)
         i = i + 1
         alpha(i) = angle
         psi(i) = SQRT(alpha(i)**2 - 0.000002*(rmxmtr - rmsfc))
         IF (psi(i) .LT. 0.0175) THEN
            angle = angle - dalpha
         ELSEIF (psi(i) .LT. 0.08) THEN
            angle = angle - dalpha*10.
         ELSE
            angle = angle - dalpha*50.
         END IF
         IF (angle .EQ. 0.)  angle = 0.000001
      END DO
      imax = i
c
c           initiate ray trace from hxmtr to sfc
c
      DO i = 1, imax
         angle = alpha(i)
         rng = 0.
         IF (angle .GT. 0.) THEN
            CALL upgo(angle, ixmtr, idelta, rng)
            angle = -alphmx
            rng = rng * 2.
         END IF
         CALL downgo(angle, ixmtr, rng)
         r(i) = rng
      END DO
c
c
      RETURN
      END

cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c
c
c
```

```
c  Name:
c
c      SUBROUTINE psirae (rk, hxmtr, rmax, alpha, psi, r, imax)
c
c  Purpose:
c
c       This subroutine generates arrays of ray launch angle, alpha,
c       grazing angle, psi, and range, r, to be used as inputs to the
c       clutter level calculations.
c
c  Inputs:
c
c       hxmtr, rk, rmax
c
c  Outputs:
c
c       alpha, psi, r, imax
c
c  Calling routines:
c
c       clutr
c
c  Routines called:
c
c       SQRT
c
c  Glossary:
c
c       alpha(*) - ray launch angle at the transmitter (radians)
c       hxmtr    - radar antenna height (m)
c       imax     - number of elements in alpha, psir, & r arrays
c       psi(*)   - grazing angle at the sea surface (radians)
c       r(*)     - range (km)
c       rk       - effective earth radius factor
c       rmax    - maximum plot range (km)
c
c  Method:
c
c       This subroutine takes radar antenna height and effective earth
c       radius and returns launch angle, alpha, and grazing angle, psi,
c       versus range for values of psi between 0.1 and 10 degrees
c       using the solution of the ray trace equations in terms of ae.
c
c
ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c
c
c
      SUBROUTINE psirae (rk, hxmtr, rmax, alpha, psi, r, imax)
c
```

```
      DIMENSION alpha(50), psi(50), r(50)
c
      ae = rk * 6371.
c
c             determine the range at which psi= .1 deg
c
      psi(1) = 0.001745
      a = 1.
      b = 2. * ae * psi(1)
      c = -2. * ae * hxmtr / 1000.
      r(1) = (-b + SQRT(b*b - 4.*a*c)) / (2.*a)
      IF (r(1) .GT. rmax) r(1) = rmax
      alpha(1) = -(hxmtr/(1000.*r(1)) - r(1)/(2.*ae))
c
c             determine range at which psi = 10 deg
c
      b = 2. * ae * 0.1745
      rmin = (-b + SQRT(b*b - 4.*a*c)) / (2.*a)
c
c             determine alpha & psi for intermediate ranges
c
      i = 1
      dr = r(1) - rmin
      DO i = 2, 45
         r(i) = r(1) - dr*i/45.
         alpha(i) = -(hxmtr/(1000.*r(i)) - r(i)/(2.*ae))
         psi(i) = hxmtr/(1000.*r(i)) - r(i)/(2.*ae)
      END DO
      imax = 45
c
c
      RETURN
      END
c
c  Subroutine push
c
c  PUSH stores elements in an array and returns.
c
c  Variable:       Description:
c
c    array        iq array to hold data elements
c    iq           Size of data array
c    nq           Number of data elements stored in data array
c    data         The data element to be stored
c
c
      SUBROUTINE push(ARRAY,iq,nq,data)
c
      real*4 data,array
      integer*2 iq,nq
```

```
      dimension array(iq)
c
c       Shift array elements down one
c     do i=iq,2,-1
      DO j=2,iq
         i=iq-(j-2)
         array(i)=array(i-1)
      END DO
c
c       Store new data element in top of array
      array(1)=data
      nq=nq+1
      IF(nq .GT. iq) nq = iq
      RETURN
      END

cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c
c
c  Name:
c
c       SUBROUTINE upgo (alpha, ixmtr, idelta, r)
c
c  Purpose:
c
c       Ray trace for upgoing rays, alpha >= 0
c
c  Inputs:
c
c       alpha, idelta, rhl(*), rml(*), ixmtr
c
c  Outputs:
c
c       r
c
c  Calling routines:
c
c       psir
c
c  Routines called:
c
c       SQRT
c
c  Glossary:
c
c       alpha   - launch angle in radians
c       idelta  - index of level in profile for evap. duct height
c       ixmtr   - index of level in profile for transmitter
c       rhl(*)  - height (m)
c       rml(*)  - modified refractivity (M)
```

```
c       r        - range (km)
c
c  Method:
c
c          An upgoing ray is traced through the successive layers of
c       the M profile to determine the range at which it reaches the
c       height of the evaporation duct.
c
c
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c
c
      SUBROUTINE upgo (alpha, ixmtr, idelta, r)
c
      DIMENSION rhl(10), rml(10)
c
      COMMON /RAYTRACE/ rhl, rml
c
       i = ixmtr
       DO WHILE (i .LT. idelta)
          dh = rhl(i + 1) - rhl(i)
          dm = rml(i + 1) - rml(i)
          dmdh= dm/dh
          IF (dmdh .EQ. 0.) dmdh = 1e-8
          sum = alpha**2 + 0.000002*dmdh*(rhl(i + 1)-rhl(i))
          IF (sum .LT. 0.0)  sum = 0.0
          alphap = SQRT(sum)
          rp = r + (alphap-alpha)/(dmdh * 0.001)
          alpha = alphap
          r = rp
          i = i + 1
       END DO
c
      RETURN
      END
```

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A model for the average sea clutter radar cross section is proposed for the Oceanographic and Atmospheric Master Library. This model is a function of wind speed (or sea state), wind direction relative to the antenna, refractive conditions, radar antenna height, frequency, polarization, horizontal beamwidth, and compressed pulse length. The model is fully described, a FORTRAN 77 computer listing is provided, and test cases are given to demonstrate the proper operation of the program.

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